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APPLICATION OF NEW TECHNOLOGY TO FUTURE CELESTIAL TRACKERS

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ABSTRACT

New developments in image sensors and optical materials has opened the door to dramatic mass and power reductions in celestial tracker designs. The rapid development of active pixel sensors (APS) has provided a new detector choice offering high on-chip integration of support circuitry at reduced power consumption. Silicon- Carbide (Si-C) optics are one of the new developments in low-mass optical components. We describe the celestial tracker needs of an Autonomous Feature and Star Tracking (AFAST) system designed for autonomous spacecraft control. Details of a low mass celestial tracker, based on a low power APS array and optimized for an AFAST system, are discussed.

Keywords: autonomy, celestial tracker, active pixel sensors

1. INTRODUCTION

increasingly discussions concerning future Solar System exploration include autonomous spacecraft. Creating an autonomous spacecraft capable of independently managing Solar System exploration requires a new look at celestial tracking sensors and systems. While conventional star trackers are typically optimized for star identification and position measurement, autonomous spacecraft will use images of planets, asteroids and other Solar System bodies, as well as stars, to make spacecraft control decisions. This strongly influences the tracker design with respect to choices in optics and detectors, and also suggests one single field of view (FOV) camera may not be sufficient. Further adding to the list of new requirements is the need to reduce component mass and power budgets. In this era of reduced funding it is increasingly important that overall spacecraft mass and power, and thus cost, be lowered.

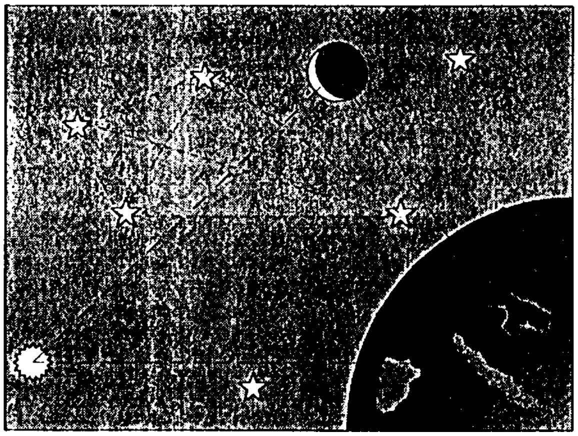


Figure 1 - Autonomous spacecraft will observe a range of celestial objects in the process of making GNC decisions. Besides stars and star fields, the celestial sensor will use centroiding and feature tracking techniques on extended objects when they are visible. Measuring parallax angles between Solar System objects and the spacecraft provides trajectory and spacecraft-to-target knowledge.

We are developing an Autonomous Feature And Star Tracking (AFAST) system [1-3] that will bring autonomous control capability to small spacecraft and provide direct cost savings to future missions. in the AFAST model followed in this paper a spacecraft would carry sufficient on-board capability to autonomously manage all spacecraft guidance, navigation and control (GNC) functions, This frees traditional ground support from extensive mission tracking and control work to one of collecting occasional status reports and, ultimately, scientific data from the spacecraft upon reaching it's target.

This paper describes the planning and development of the imaging hardware component, a celestial tracker, that supports AFAST image requirements. The celestial tracker described here provides vision to an autonomous spacecraft GNC system and is capable of imaging stars, Solar System bodies, and body features. The focus of this paper is on the imaging needs of an autonomous spacecraft GNC system and the development of a celestial tracker that meets those requirements. The starting point is a discussion of an autonomous mission scenario and the demands it puts on a celestial tracker.

2. Celestial Tracker Requirements for Autonomous Spacecraft

Using the AFAST mode] a typical mission can be broken down into several unique phases (figure 2). These phases include: a departure phase - what happens just after launch and before cruising to the target, a cruise phase - what happens along the way to the target, and an encounter phase - when the primary objective science is carried out. An elaboration of this sequence can be made for cases where multiple targets are encountered, orbit insertion is required, and even for landing and sample-return missions. In each case the demands on the imaging system are basically unchanged ‘he ‘nCounter with ‘he target.

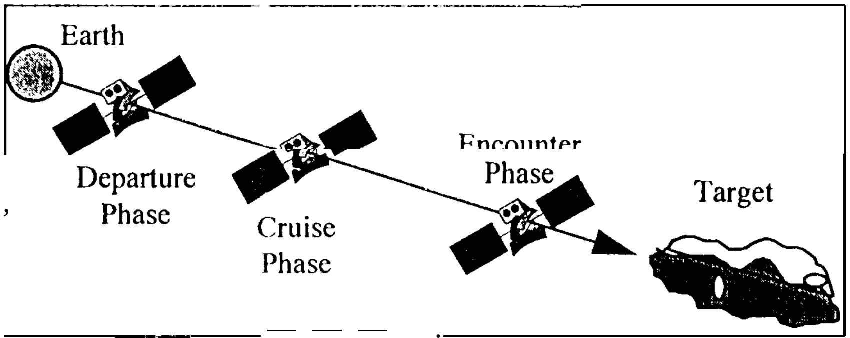


Figure 2- Within the A FAST model a typical mission can be broken down into three phases covering departure from the Earth, travel to the target, and

In short it must be capable of both wide and narrow FOV imaging at moderate to fast data rates, depending on the mission phase and objectives. Thus we have taken the simplest case here, the three phase mission mentioned above, as a starting point for the camera design inputs.

A key idea in autonomous spacecraft control is to take advantage of existing scene information to make course trajectory corrections without interactions with ground support facilities. This means that during each phase of the mission the celestial tracker must provide images that contain information specifically useful in spacecraft-to-target position determination, as well as images useful in generating conventional spacecraft attitude information. Typically this will be done by making parallax observations of Solar System bodies to generate spacecraft-to-target determinations and by more conventional methods (star field imaging) for attitude determination. During each phase of the mission targets of special interest are available that aid in spacecraft position and trajectory determination. A brief discussion of each of the three mission phases will help to outline the challenges confronting the celestial tracker and to list the available targets. By considering these phases and related image scenes a list of camera requirements emerges,

2.1 Departure Phase

After launch a spacecraft must determine it’s orientation and take steps to stabilize itself. During this time the Earth, Moon and Sun are available, along with background stars, for accurate determination of orientation and position. Using these bodies demands that the celestial tracker be capable of working with such bright and extended objects. To accomplish this it must be capable of providing useful images for body edge detection and centroiding, feature identification and tracking, as well as imaging relatively faint stars near the limb of a bright body. It must have sufficient dynamic range and a wide field of view (FOV) to produce useful images. From tracker images one can use center of mass data and limb detection from the Earth and Moon, as well as parallax measurements as the Earth and Moon are viewed from different angles over time to calculate spacecraft position relative to the Earth.

Several tracker requirements emerge quite rapidly. First, the celestial tracker FOV must be large enough to provide useful images of extended bodies when they are nearby (the Earth just after launch for instance). One solution is to provide a FOV of order 25 to 40 degrees. This would allow the celestial tracker to image much if not all of a nearby body. Typically an increase in FOV also means a decrease in sampling resolution (sky area per pixel) and will put more demands on the software to extract accurate position data. The second camera requirement to emerge is the need for adequate dynamic range and image saturation control (antiblooming) at the high end of the dynamic range. To measure parallax with extended Earth or Moon disks against background star fields, both a large dynamic range and saturation control must be available, Images of such scenes must preserve planet center-of-mass information (i.e. show the disk or limb of the body), while still providing useful star images with these planets in the FOV. In some cases there might be as much as 10 to 20 stellar magnitudes (104 to 108 ratio in brightness) of difference between the brightness of a nearby planet and the brightest stars. Ideally this would be managed in such a way that only a single frame be required so that normal spacecraft motion is not an issue.

[1] Perhaps the most extreme demand comes from the very wide FOV desirable in an autonomous landing scenario,

2.2 **Cruise Phase**

During the cruise phase the celestial tracker will look away from the inner Solar System[2] and seek out new navigation targets. These targets consist of asteroids, comets, and any bright or optically resolvable planets along the cruise route. Again a celestial mechanics problem is solved (figure 3) for spacecraft-to-target position, taking advantage of the parallax seen by the spacecraft as it and these targets move relative to each other. The problem becomes more difficult now as the observed targets, mostly asteroids, are typically not bright. Further adding to the problem, the quality of the asteroid's ephemeris may not be as accurate as those for the major Solar System planets.

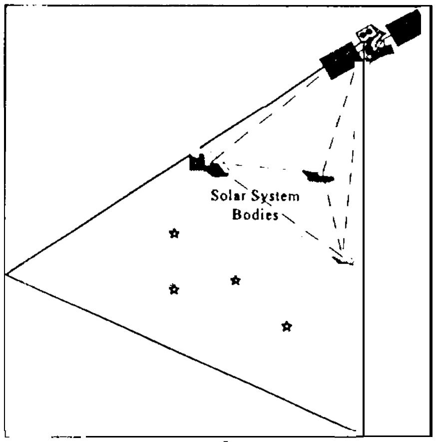


Figure 3 - During the cruise phase of the mission asteroids can be imaged to provide GNC information.

The wide FOV described in the departure phase would serve well for pointing the spacecraft at the region of the sky where an asteroid of interest is located. However, this wide FOV is not well suited to making the precision parallax measurements required for autonomous spacecraft control. A better choice for measuring parallax would be a narrow FOV of order a fraction to a few degrees in diameter providing better spatial resolution. ALso, one must consider the tracking and spacecraft stability requirements when integrating on faint asteroids.

2.3 **Encounter Phase**

As the spacecraft approaches it's primary science target the encounter phase begins. At this point the target emerges from the background stars first as a conspicuous point source (relatively bright and moving against the background) and then as a resolvable object (figure 4). During this phase of the mission the celestial tracker must provide images adequate for point source centroiding, extended body centroiding and finally feature tracking as the range to the target decreases.

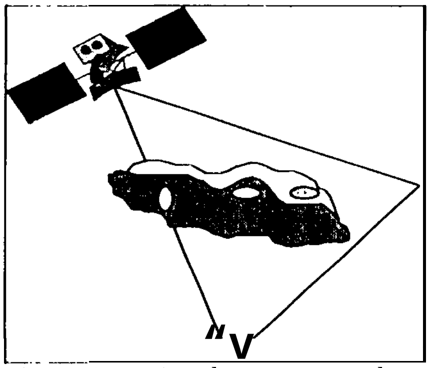


Figure 4- During the encounter phase of the mission the science target may be used to gather GNC information.

In this phase the problem of determining spacecraft-to-target vector information is compounded with the additional requirement of providing correct science instrument pointing during the encounter. During this phase it is likely that a narrow FOV would be most useful at the start of the encounter when the target is still rather distant. As the spacecraft nears the target a hand-off to the wide FOV would allow extended body centroiding and feature tracking as the apparent size of the target swells in the image. Again dynamic range and image saturation issues must be considered to generate useful images.

3. CELESTIAL TRACKER DESIGN

From the discussion above of the three mission phases it becomes apparent that the long standing dilemma confronting conventional star tracking camera designs, wide FOV vs. narrow FOV, does not go away when considering the needs of an autonomous spacecraft. Instead it seems that *both* wide and narrow FOVs are called for to satisfy all imaging needs. Before moving on it should be mentioned that several less conventional and potentially risky solutions to this dilemma can be mentioned, For instance one might satisfy the need for both narrow and wide FOV by building a narrow FOV system and feeding it with an articulated input mirror. Another solution to the FOV dilemma would be to incorporate an existing narrow FOV science instrument into the GNC system. By moving a defocusing, element into the optical beam, the normally sharp, well focused science image can be slightly defocused for star tracking purposes.

At this time the authors prefer to consider the celestial tracker dedicated to GNC functions, and do not involve the use of science instruments or special unconventional instrument features in the design, 'I'his helps to clarify the issues that are strictly celestial tracker and GNC, baseline the minimum camera requirements and separate risk issues. We leave open the combination of science and GNC instruments and special techniques for future discussions.

[2] Of course the Sun will continue to be a reference point when needed,

Table 1 lists the celestial tracker requirements highlighted in the discussion of each phase of the mission. Exact values for some parameters are impossible to list at this time. For instance the choice in spatial accuracy of the tracker is driven by a number of mission parameters including science requirements and inherent spacecraft stability to name just two. It is safe to assume that parameters like spatial accuracy will be optimized in a manner according to mission requirements.

Celestial Tracker Parameter	Departure Phase	Cruise Phase	Encounter Phase
Available GNC Targets	Earth, Moon, Sun, bright planets, background stars	Sun, bright planets, asteroids and comets, background stars	Sun, bright planets, science target, background stars
FOV Required	wide - extended bodies,'- multiple bodies, star ID and fields. narrow - resolving distant extended bodies.	wide - star ID and fields, locating asteroids. narrow - asteroid parallax, resolving distant extended bodies.	wide - star ID and fields, locating science target, feature tracking on science target. narrow - feature tracking on target at long distance.
Dynamic Range	very high (1 OX or higher) - faint stars near bright bodies.	high - faint asteroids near bright stars.	high - bright science target and dark features.

Table 1

To satisfy the needs of the three mission phases described earlier, a baseline celestial tracker can be sketched out. Figure 5 shows one possible arrangement of both a narrow and a wide FOV camera to form a complimentary system. This layout provides two separate sets of optics and image sensors, but shares a common array controller and image processor. Mass can be restricted in the wide FOV camera by selecting a small aperture, very wide FOV optic, say 20 to 40 degrees, allowing, it to work exclusively with bright objects (visual magnitude 6 and brighter). For the narrow FOV camera special effort must be made to reduce mass.

Using the layout shown in figure *6* each of the mission phases are supported, During the departure phase the wide FOV camera is used to view the shape and features of nearby bodies (Sun, Earth and Moon). Over the cruise phase the wide FOV camera would be used to view the inner Solar System and to point the narrow FOV at cruise phase targets (asteroids). When in the encounter phase both the wide and narrow FOV cameras would be used to point the science instruments at the target and to maintain spacecraft stability.

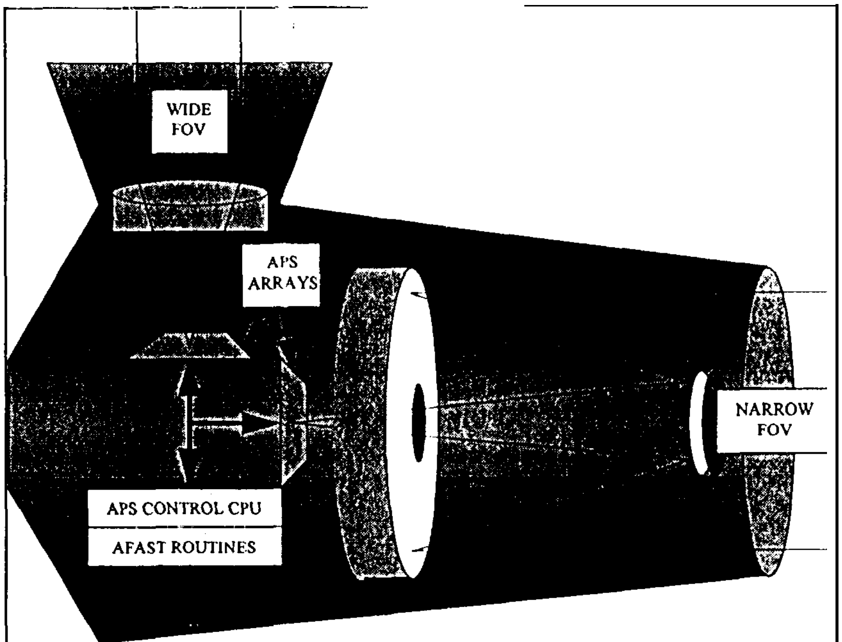


Figure 5 - A simplified layout of the celestial tracker might incorporate a dual FOV system. A single APS processor would control both arrays (only one powered at any given time) managing the readout sequencing and simple image processing. It would also be capable of running AFAST routines on images. The narrow FOV might be a fraction to a few degrees on a side providing high spatial sampling accuracy. The wide FOV might be 20 to 40 degrees on a side and be optimized for feature tracking on nearby extended bodies and for star identification.

3.1 **Detector Choices**

The celestial tracker described here has many characteristics in common with traditional star trackers. In particular both trackers require pixelated image sensors (area arrays) with low noise and stable geometry. Increasingly the charge-coupled devices (CCD) has become the detector of choice for most star trackers. We too see the CCD as a reasonable choice for this celestial tracker and consider it a serious option. However, as stated earlier, reducing power consumption is a very strong design driver and motivates us to consider all options.

In the last few years a new family of imaging arrays called active pixel sensors (APS) [4] have matured from concept to real sensors and are now available for experimentation in a tracker role. APS arrays share many similarities with CCDS including pixelated architectures, photon response curves (APS are Si based detectors), and the potential for low noise performance (under 20 electrons). In other ways they differ significantly. For instance the CCD, being a charge transfer device, is sensitive to charge transfer efficiency (CTE) degradation as a symptom of radiation damage, while the APS is less sensitive to radiation damage because it does not transfer charge microscopically across the array (figure 6).

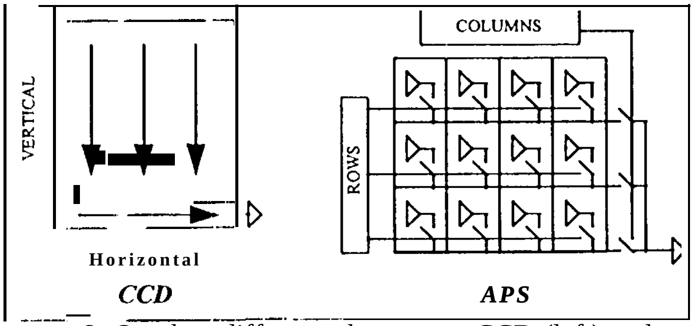


Figure 6- One key difference between a CCD (left) and an APS (right) is that the CCD transfers image charge to an output amplifier (one or several), while the APS places a sampling amplifier *within* each pixel.

Perhaps the biggest difference between the two detectors, and the most obvious advantage of the APS over the CCD for AFAST, is the CMOS nature of the APS. Because the APS uses CMOS design and fabrication methods, common to memory and digital IC manufacturing, an APS design may contain a great deal of support circuitry ***on-chip*** and with low power designs. Already APS arrays that include array control circuitry (pixel addressing and clocking), special analog signal processing circuits, filter circuits and multiple ADCS, all on-chip, have been demonstrated [5-7]. This compatibility to on-chip circuit integration allow APS-based camera designers to reduce circuit board space, improve performance and significantly reduce power consumption compared to CCD-based designs.

It should be made clear that, while the APS has many features that make it more attractive than the CCD, it is not perfect and brings its own challenges to the celestial sensor design. Of primary concern with the APS are the fill factor and gate structure issues and how they impact centroiding. Because the APS places active circuit elements (transistors) within each pixel, a large percentage of the overall pixel area is not active in signal collection. The resulting fill factor, typically between 25% to 45?4., directly impacts the spatial sampling capability of the ASP. The pixel structure complicates the sampling of the image scene (point spread functions) by creating a non-uniform response across the pixel. Further, placing an amplifier in each pixel implies a unique amplifier gain for each pixel.

The issue of pixel fill factor and gate structure can be addressed, though not completely resolved, in several ways. One way of improving fill factor is to apply a microlens to the surface of each pixel [4]. This boosts the fill factor into the range of 50% to 70%. One would have to consider the problems that the microlens brings to the system such as risk of de-lamination and degradation in the space radiation environment. Another way to address the pixel structure issue is to optimize pixel layout geometry. It may be advantageous to find an optimum pixel gate structure geometry that constrains sampling issues to only one axis (row or column direction). For instance an arrangement that creates two rectangles, a collection region and an amplifier region, would constrain the gate structure problem to one axis.

Additional improvement will be found by simply increasing, the input optical spot size such that more pixels sample the image. For the case of centroiding on a stellar image this method will help a great deal. Because of the inherent low-power consumption of the APS and it's direct pixel access architecture, it is conceivable that matching a very large format array, of order 2048x2048 pixels for example, to the proper optics will relieve the sampling problem. Regarding the problem of pixel-to-pixel gain variations, with proper design the difference between the APS amplifier gain non-uniformity and the problems of pixel-to-pixel non-uniformity seen in CCDS [8] need not be great. Despite the issues of gate structure and pixel non-uniformity, we feel that the APS is an interesting detector choice and warrants further testing. This **does not exclude** using a CCD in the celestial tracker if the APS technology is found to be immature or inadequate for our needs.

We are developing an APS array design optimized for the needs of the celestial tracker described here. This development cycle includes several key steps. First a series of lab tests will be conducted on an existing "generic" APS to characterize fundamental performance. Secondly, the same APS array will be used to image the night sky. This test will help verify that the APS under near-actual conditions. Finally, depending on the outcome of the first two steps, an optimized APS design will be completed for use in a celestial tracker. "

3.2 Lab and On-Sky Testing

To help refine the baseline features of a celestial tracker APS design we are conducting laboratory testing of an existing APS array. The array is operated over a range of temperatures (-4OC to +30C) and controlled with a programmable array controller. Figure 7 describes the test system layout including the programmable array controller and the image processing and analysis tool set.

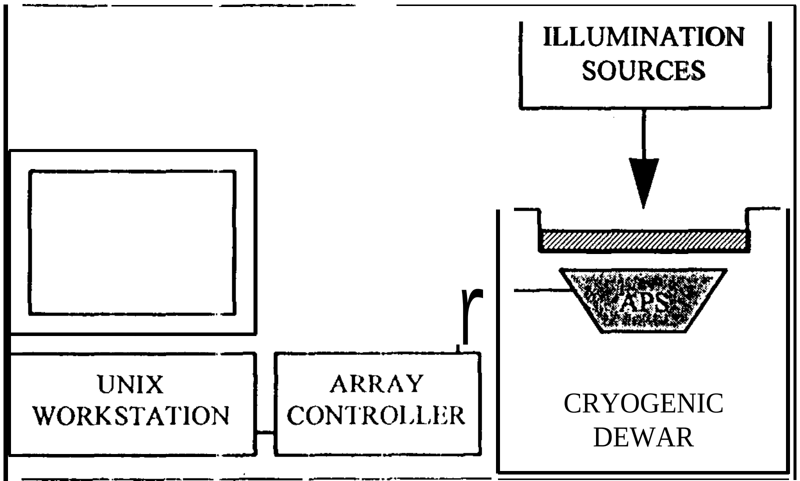


Figure 7 - A programmable imaging array controller will be used to operate an APS and conduct both lab and on-sky tests.

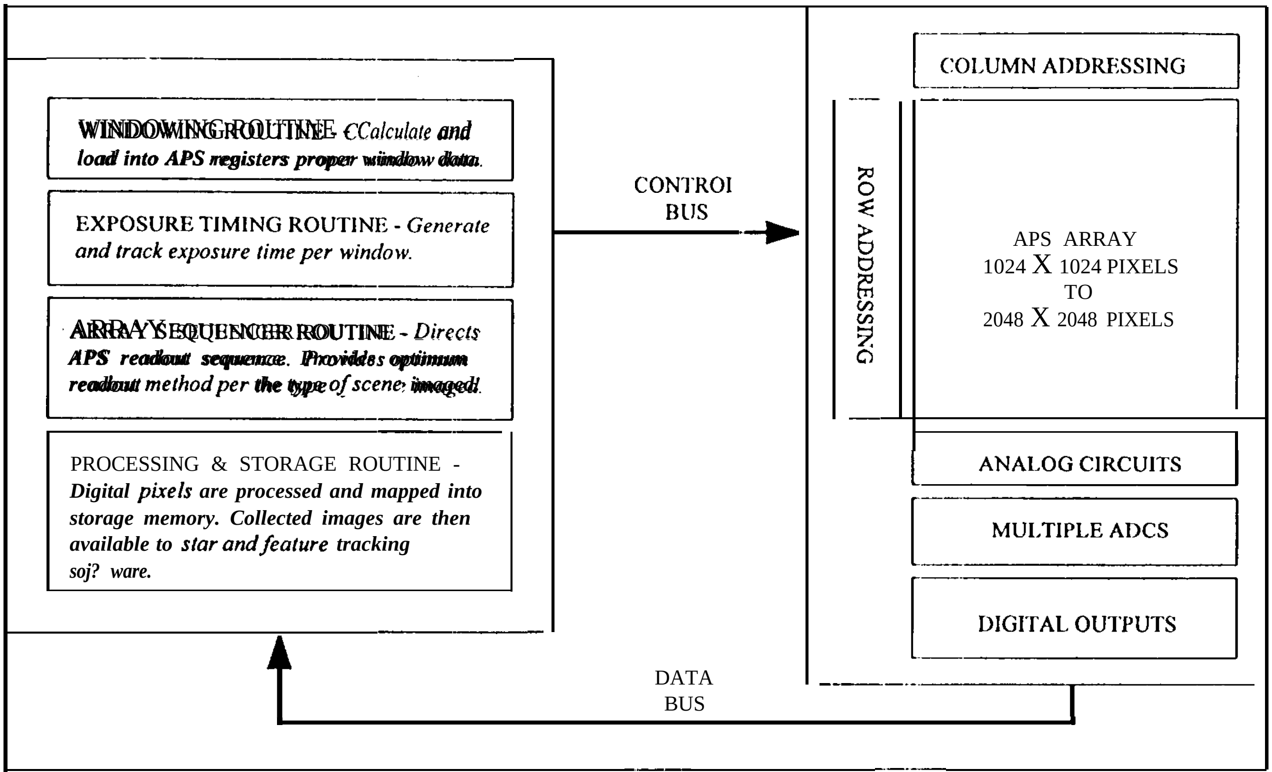
This test system allows us to adjust and test various aspects of APS operation including readout windowing, array clocking and video sampling techniques with only minor changes to the control software. We will measure dark current, pixel-to-pixel variations, pixel amplifier and fixed pattern noise over a range of temperatures and operating modes.

In addition to supporting the lab work described above this same test setup also serves as a platform for testing the APS directly on the sky. We will image a host of celestial objects at JPL's Table Mountain Observatory (TMO) under conditions that simulate a set of autonomous spacecraft GNC situations, A key piece of the test equipment is a large set of AFAST software routines [1] which will be applied directly to images generated at TMO. These routines are designed to locate and track the limb of a planet, find the center of mass of a planet's disk, measure star positions near the limb of a planet, and, of course, conduct conventional star identification and position measurements. During the on-sky tests we will experiment with different windowing sizes and placements, readout sequences and rates, and output data compression methods to explore optimal ways of using an APS in conjunction with AFAST software. An assortment of interchangeable camera lenses completes the test system and provides a range of images scales.

The results of these lab and on-sky tests will directly feed into the design of an AFAST-specific APS array. As mentioned earlier, a great deal of support circuitry can be placed on-chip in the APS design. Our tests are designed to evaluate the control circuit options before committing to a final APS design. From these tests we will better understand a range of generic APS features, details of applying an APS to celestial scene imaging, and how well the APS images work with AFAST software, From here we are ready to approach the next step of developing an APS array optimized for AFAST work.

3.3 Celestial Tracker APS Design

Without performing any APS tests we already have a good idea of the general features we want in an APS design, From the discussion of the celestial tracker requirements in each mission phase, and from conventional star trackers, we have a list of desirable features to add to the APS. For instance, we know that windowed versus full frame readout helps improved data rates and reduce image storage problems. We know that low noise, large dynamic range and on-chip video sampling are desirable features. Further we know that pixel fill factor, the actual amount of the pixel collecting photo-signal, needs to be maximized If in addition the optics are considered in the solution to the APS gate structure problem, then it is likely that a large array format will be of interest (perhaps as large as 2048x2048 pixels).



igure 9- One possible functional layout for the celestial tracker detector would include an APS with on-chip pixel addressing and video sampling, and an off-chip APS controller unit either in the form of a processor (software based) or in the form of an ASIC (hardware based). Ultimately the APS control module might be "embedded in the APS.

Figure 9 above shows one possible functional layout of the APS design considered here. In this layout a processor-like block is shown managing several APS control functions including exposure timing, window selection and readout sequencing for the array. In practice APS control might be done either on the APS chip by adding more digital logic to the APS design, or off-chip with a separate processor or ASIC. The best choice, on-chip or off-chip, will depend on the number and complexity of the control tasks, and on how much flexibility is required in the tracker. Initially we consider using an off-chip processor to control the APS as the logical choice. First, this gives us more flexibility by placing APS control in the software domain where it is more easily modified, and secondly, we can shift APS management onto the APS later if there is a demand for it. The resulting design provides a completely digital imaging array (digital control inputs and digital pixel data outputs) running at low power (5 volts at a few hundred milliwatts). The addition of a CPU managing APS control and image processing, and some image memory completes the celestial tracker electronics.

3.4 **Optical Elements**

While the discussion of mission phases above leads to a fairly clear picture of detector requirements, the details related to optics are not as straight forward. Partly this is because the choice of an APS, given the features of its pixel structure, directly impacts the demands on the optics, and partly because of the desire to reduce mass. However, from the discussion of mission phases and overall camera design it is apparent that two different FOV camera optics are required - one narrow and one wide. For the wide FOV camera we see an optical design that uses refractive elements as being most practical.

For the narrow FOV a conventional all-reflecting camera design, such as a catadioptic or cassegrain design, can be pursued. These families of reflecting telescopes are well suited to FOVs of order a fraction to many degrees on a side. Here the mass issue is more of a concern in that the primary mirror in the narrow FOV camera must have sufficient aperture to allow imaging of faint asteroids during the cruise phase of the mission. This desire for aperture in turn drives Up the mass and, using conventional glass optical elements, might prove prohibitive. To address the mass constraints we are exploring the use of low-mass Silicon-Carbide and Beryllium optical elements. These materials offer the potential for significant mass reduction and even athermal design features. For now we are directing our efforts toward detector issues, but will, at the conclusion of that effort, concentrate on development of the optics.

4. Summary and Conclusions

In this paper we have discussed a multiphase mission scenario for autonomous spacecraft that puts specific demands on the celestial tracker. Further we have outlined the way a celestial tracker might be used within the Autonomous Feature And Star Tracking (AFAST) solution to autonomous spacecraft GNC. In its simplest form this celestial tracker would use two FOVs, one wide and one narrow, to help produce spacecraft-to-target trajectory information. To reduce power consumption active pixel sensors (APS) are being considered as the imaging array. Silicon-Carbide and Beryllium optical elements are being explored to reduce camera mass. The celestial tracker concept presented here is in an early phase of development and will undergo both lab and on-sky tests in the near to verify key elements in the design. We are strongly committed to building alliances with industry partners who can bring their expertise to bear on celestial trackers and help us ready it for use in the near future.

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